# Multijunction Photovoltaic Technologies for High Performance Concentrators

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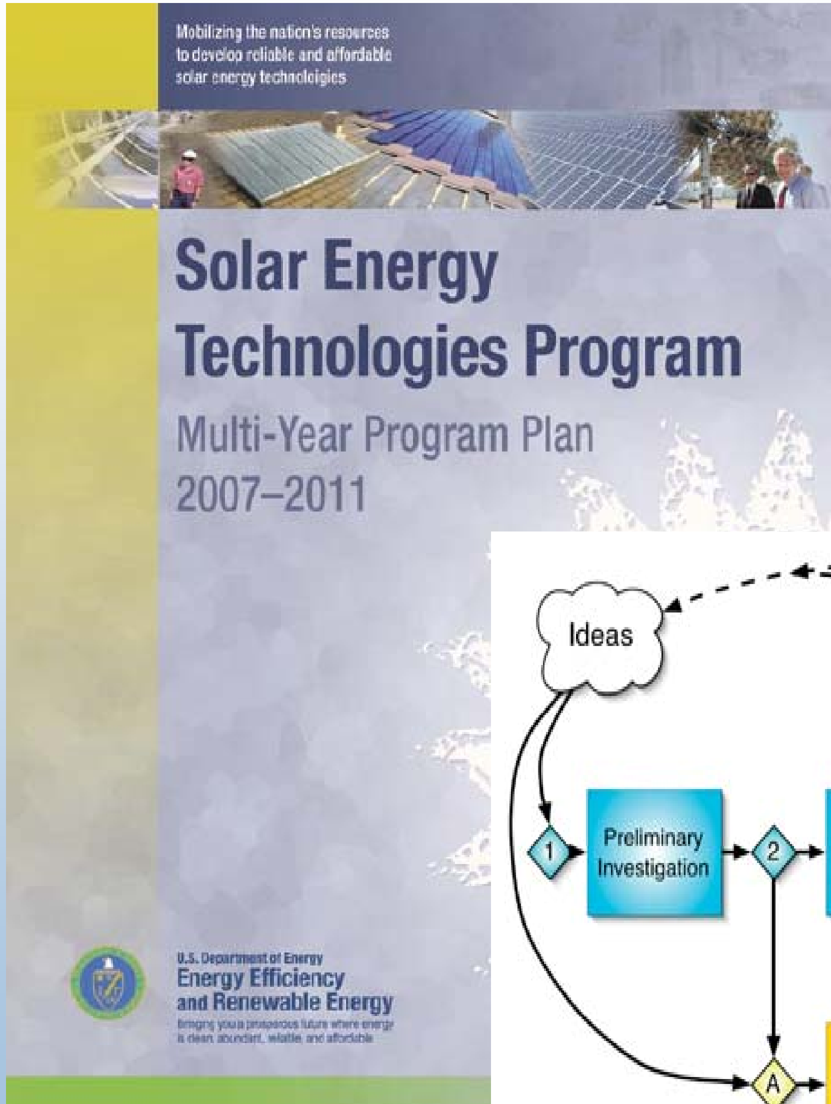
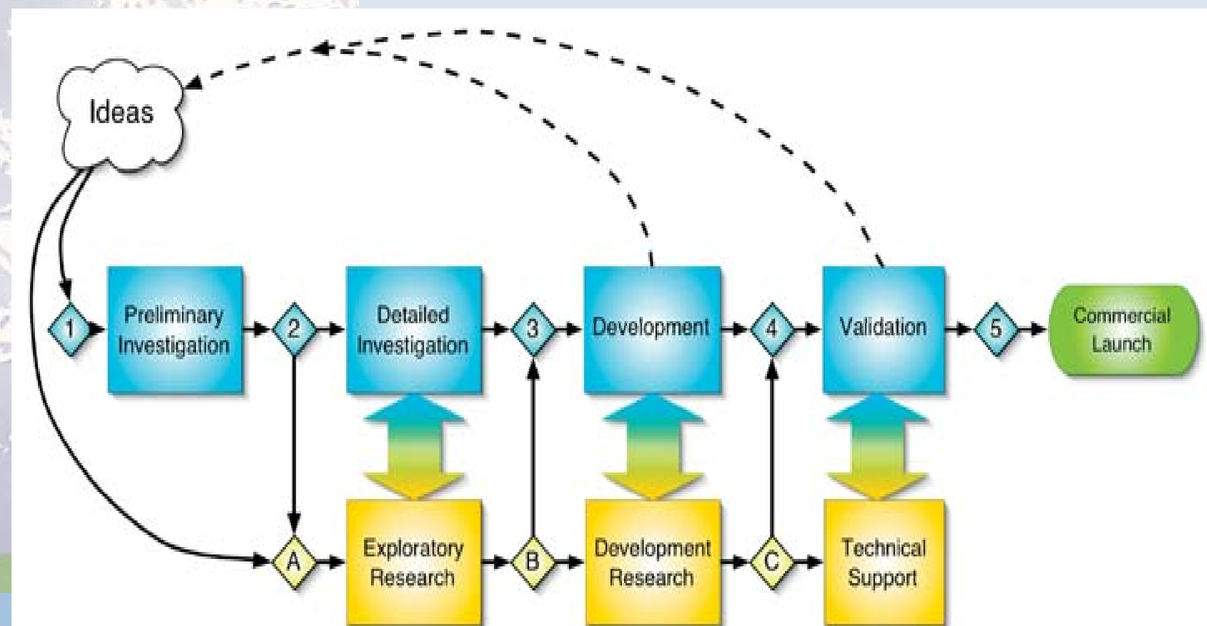
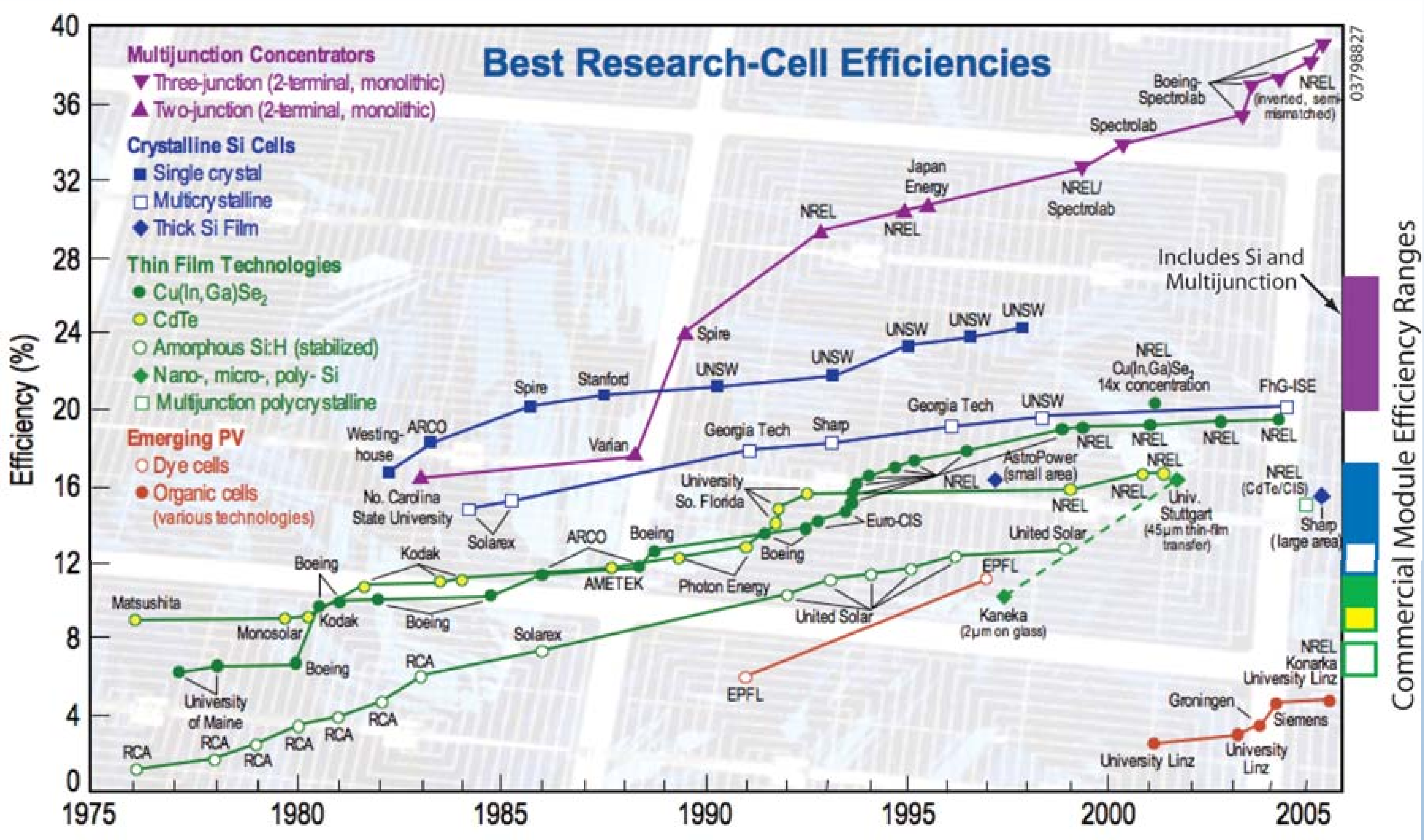
High Performance Photovoltaic Project
National Center for Photovoltaics
National Renewable Energy Laboratory

NREL/PR-520-39866
Presented at the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4) held May 7-12, 2006 in Waikoloa, Hawaii.

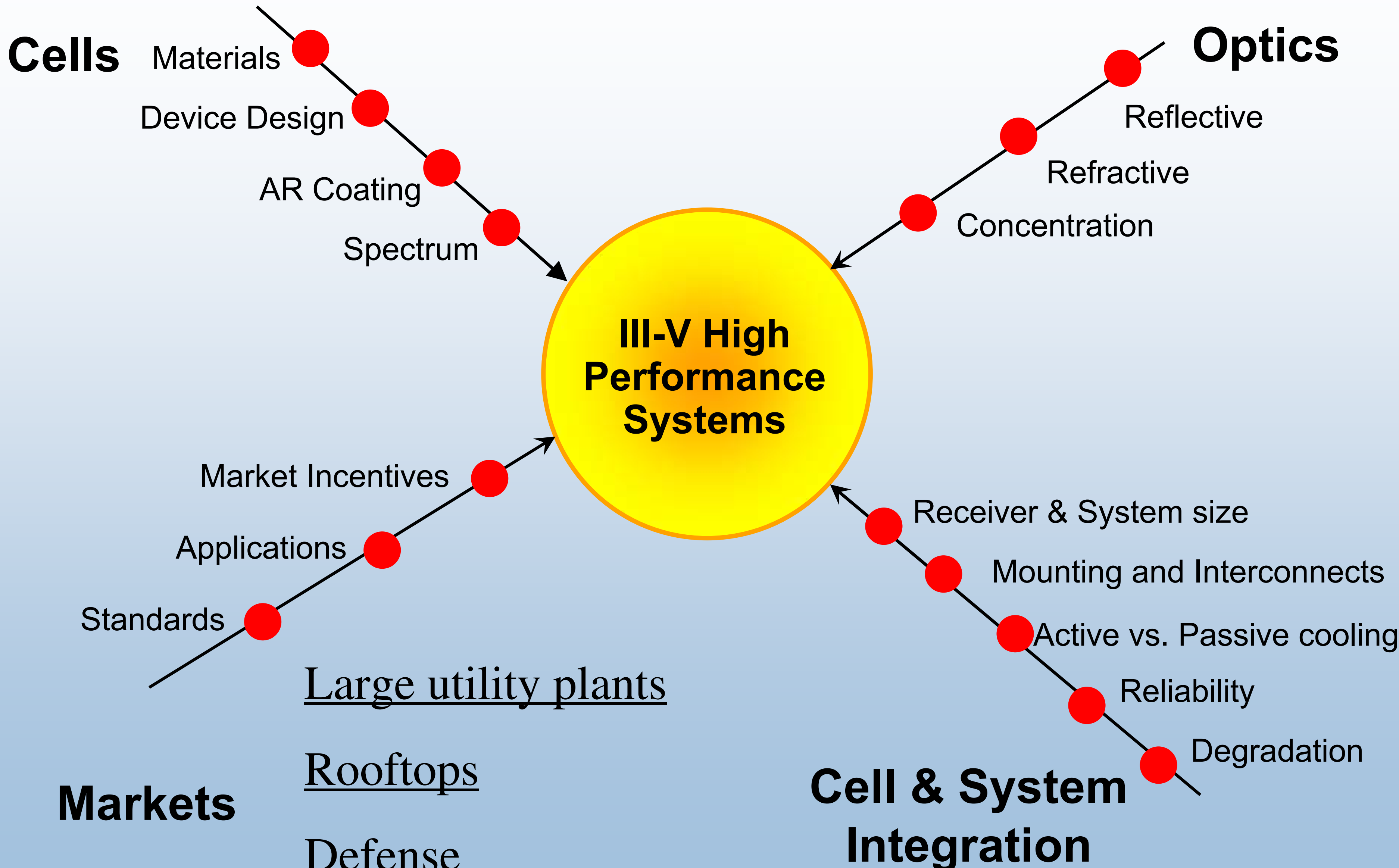



- Systems Driven Approach
- Technical Improvement Opportunities (TIOs)
- Stage Gates
- Solar Advisor Model (SAM)




Best Research-Cell Efficiencies
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si Film
Thin Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly- Si
Multijunction polycrystalline
Emerging PV
Dye cells
Organic cells (various technologies)
Efficiency (%)
Includes Si and Multijunction
Commercial Module Efficiency Ranges
037798827

# *High Performance Concentrator PV Project*



# Efficiency Impact on Levelized Cost of Energy (LCOE)

| | | | | |
|---|---|---|---|---|
| System Size | MW | 10 | 12.5 | 16 |
| Module Price | $\$/W_{dc}$ | 4.13 | 3 | 1.56 |
| Cell Efficiency | % | 26 (Si) | 32 (III-V) | 40 (III-V) |
| Module Size | $kW_{pdc}$ | 40 | 50 | 64 |
| Module Efficiency | % | 20 | 25 | 32 |
| Installed System Price | $\$/W_{dc}$ | 5.95 | 4.3 | 2.52 |
| Levelized Cost of Energy (LCOE) | $\$/kWh_{ac}$ | 0.15-0.27 | 0.10-0.15 | 0.06-0.11 |

Reference: DOE MYPP 2007-2011: from Table 3.1.6-5

# High Performance Concentrator PV Subcontracts (2004–2007)

| Subcontractor | Concentrator Cells Project Title | 3-Year Funding Total |
|---|---|---|
| Spectrolab, Inc. | Ultra-High-Efficiency Multijunction Cell and Receiver Modules | $837,000 plus $126,000 cost share |
| California Institute of Technology | Four Junction Solar Cell with 40% Target Efficiency Fabricated by Wafer Bonding and Layer Transfer | $525,000 |
| University of Delaware | Novel High Efficiency Photovoltaic Devices Based on the III-N Material System | $450,000 |
| Ohio State University | Optimized III-V Multijunction Solar Cells on Patterned and Ge Substrates | $465,000 |
| University of Delaware | Theoretical and Experimental Investigation of Approaches to >50% Efficient Solar Cells | $300,000 |

# High Performance Concentrator PV Contracts (2004–2007) *cont.*

| Subcontractor | Concentrator Systems Project Title | 3-Year Funding Total |
|---|---|---|
| Amonix, Inc. | Design and Demonstration of >33% Efficient High Concentration Module using >40% III-V Multijunction Devices | $836,000 plus $89,000 cost share |
| JX Crystals, Inc. | Toward 40% Efficient Hybrid Multijunction III-V Terrestrial Concentrator Cells | $450,000 |
| Concentrating Technologies, LLC | A Scaleable Reflective Optics High Concentration PV System | $450,000 plus $470,000 cost share |
| SunPower Corporation/JX Crystals | Low Concentration PV System Prototype Assessment of a 3x Mirror Module with SunPower’s 20% Efficient A-300 Solar Cell | $65,000 |
| Arizona State University | Development of IEC Design Qualification Standard for Concentrator PV Modules | $100,000 |

# Ultra-High-Efficiency Solar Cell and Receiver Module

PI: Richard R. King & Raed A. Sherif, Spectrolab, Inc.

**• Research Objectives:**
This program aims to develop ultra-high-efficiency triple-junction solar cells and to demonstrate a working robust receiver packages.

**• Approach:**
1. High-efficiency GaInP/GaInAs/Ge triple-junction concentrator solar cells

2. Metamorphic, lattice-matched, and mechanically stacked solar cells

3. Analytical modeling and long-term experimental evaluation of different receiver designs

**• Broader Impact:**
- Pushing III-V multijunction cells to ever higher efficiency lowers balance-of-module and balance-of-system costs, making concentrator PV one of the most cost-effective renewable electricity sources.
- Long-term receiver reliability studies lead to widespread implementation of and confidence in concentrating PV.

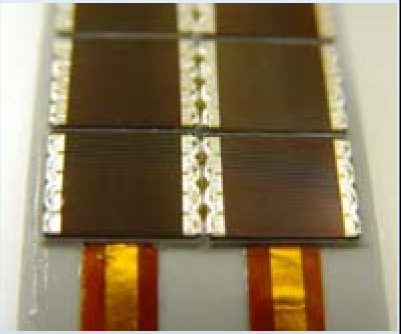
**• Significant Results:**
- 39.0% (lattice matched) and 38.8% (lattice mismatched) concentrator cells
- One year of receiver tests @ 220 suns with no change in performance.

**• Graphic:**

Ultra-High-Efficiency Solar Cell

assembly developed for distributed point
such as Fresnel lens parquet primary optics.
l assembly for dense array mirror systems
ing parabolic dish optics.

(a)



(b)

# Title: Four-Junction Solar Cell with 40% Target Efficiency Fabricated by Wafer Bonding and Layer Transfer

## PI: Harry Atwater, California Institute of Technology

## • Research Objective:

Demonstrate a 40%-efficient, 1-cm$^2$ solar cell optimized for terrestrial application using a nonlattice-matched tandem heterojunction fabricated by wafer bonding and layer transfer fabrication.

## • Approach:

1. Wafer-scale synthesis of InP/Si, Ge/Si and GaAs/Si transferred epitaxial template films by layer transfer fabrication.
2. Grow high-quality epitaxial compound semiconductor 2-junction subcells and double-heterostructures in (InGaP/GaAs/Ge/Si and InGaAsP/InGaAs/InP/Si) on transferred epitaxial template layers.

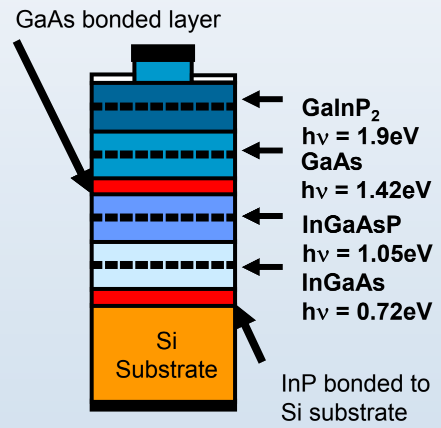
## • Industry Impact:

Active ongoing research projects with Spectrolab is a significant component of this program; Spectrolab is fabricating MOCVD double-heterostructures and pn junction solar cells on the epitaxial templates from Caltech.

## • Significant Results:

- Wafer-scale layer transfer of Ge/Si and InP/Si templates achieved at the 50-mm wafer diameter
- Less than 1 nm roughness and less than 0.1 ohm-cm$^2$ interface resistance for Ge/Si and InP/Si
- Fabricated active GaInP and GaAs double heterostructures with about $10^7$/cm$^2$ defects on Ge/Si templates

## • Graphics:




*Above:* Schematic of 4-junction solar cell with bonded layers.
*Above right:* Bonded InP/Si film on 50 mm wafer

# Novel High-Efficiency Devices Based on the InGaN Material System

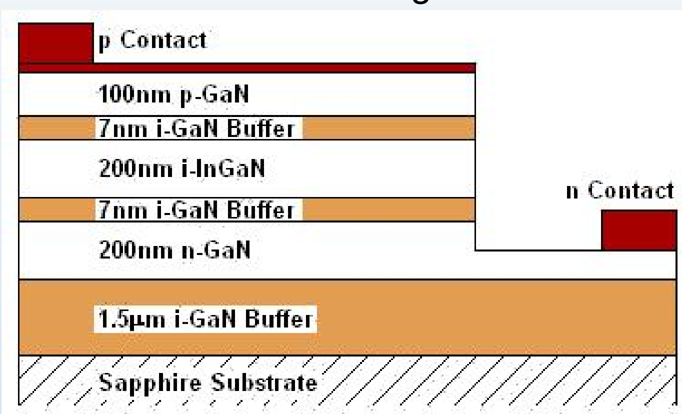
## PI: Christiana Honsberg, University of Delaware

## • Research Objective:

To demonstrate high-performance tandem solar cells based on the InGaN material system.

## • Approach:

- High bandgap: Develop GaN and In-lean InGaN p-i-n and quantum well solar cells.
- Low bandgap: Develop understanding of In-rich InGaN materials grown on Ge.

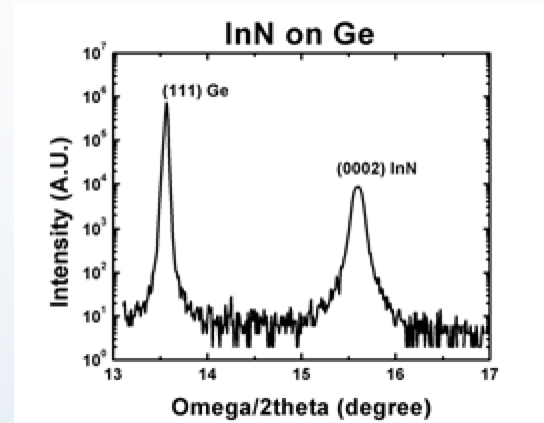



## • Industry Impact:

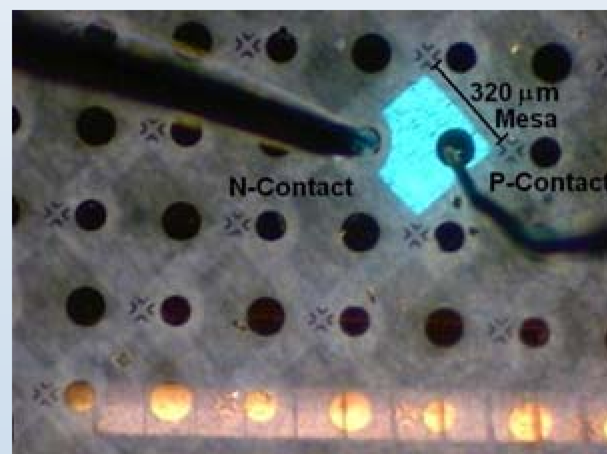
- InGaN grown on Ge and Si could offer a <u>continuum of bandgaps over the solar spectrum,</u> offering path to high-efficiency, low-cost tandem solar cell in one alloy.

## • Significant Results:

- GaN solar cells with external QE with >10% demonstrated when measured through metal Au contact.
- InGaN solar cells with 7% In shows 2V Voc, dominated by radiative defect channel
- Growth of InN demonstrated on Ge, with AlN or Al as a buffer




## • Graphics: Emission from In-lean InGaN p-i-n solar cell



# Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates

**PI: Steven A. Ringel, Ohio State University (MIT subtier contractor)**

## • Research Objectives:

Develop and demonstrate the use of novel 3-D substrate engineering in Si and Ge to achieve spectrum-optimized $E_g$ profiles leading to > 40% III-V multijunction concentrators on Si or Ge

## • Approach:

1. Grow, characterize, and optimize InGaAs/Ge and InGaAs/SiGe/Si substrates that incorporate both lattice grading and patterning to achieve ideal and tunable substrate lattice constants suitable for super-efficient III-V concentrators.

2. Grow and fabricate solar spectrum-optimized InGaP/InGaAs double- and InGaP/GaAs/SiGe triple-junction concentrators on 3-D engineered Si and Ge wafers.

3. Compare lattice-matched and lattice-mismatched III-V cells on engineered substrates.

## • Industrial and Broader Impact:

- Combining high-performance III-V PV concentrators with low-cost Si substrates exploits advantages of both to achieve $/W goals

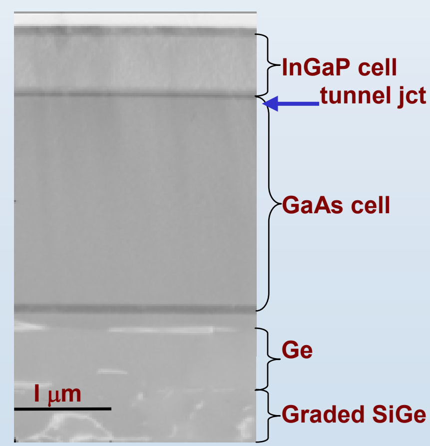
- Identical materials science has already achieved communication-band infrared and visible laser diodes on Si; combined with > 2 V cells on Si, this opens door to self-powered systems on Si chips

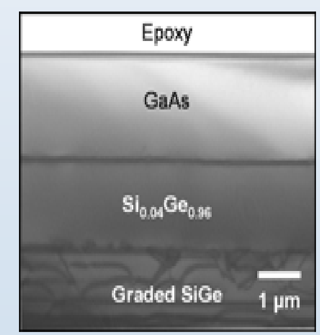
## • Significant Results:

- First III-V dual-junction cells grown on Si with $V_{oc}$ > 2 V
- First "tuned" lattice constant Si substrates for ideal III-V growth on Si. Achieved by using $Si_{.04}Ge_{.96}$ termination
- Optimization of the upper SiGe grade has reduced Ge/SiGe/Si substrate dislocation density reduced to record $6 \times 10^5$ $cm^{-2}$
- Avoided all mismatch-related defects, such as threading dislocations and anti-phase domains

## • Graphics:

***Below:*** X-TEM of InGaP /GaAs DJ cell grown and fabricated on Si using SiGe. ***Right***: X-TEM of GaAs grown on perfectly lattice-tuned $Si_{.04}Ge_{.96}$.



# Design and Demonstration of a Greater than 33% Efficient High-Concentration Module Using >40% III-V Multi-junction Devices

## PI: Kenneth Stone, Amonix Inc.

AMONIX

## • Research Objective:

To design and fabricate a module that will use >40%-efficient multijunction solar cells. It is envisioned that such a module will be 33% efficient.

## • Approach:

1. Design packing for the Ge substrate based multijunction solar cells.
2. Test packaged cells under a Fresnel lens.
3. Characterize different cells / package / lens configuration.
4. Design and construct 33%-efficient modules, to be tested on-sun, not in the laboratory.

## • Industry Impact:

The success commercialization of systens exceeding 33% will redefine the solar energy market—extremely tough competition for any other technology in concentrators or flat-plate or in the foreseeable future of photovoltaics

Paradigm shift in installed system cost – $3/W is imminent—leap into the utility market.

## • Significant Results:

- Solar cell integration significantly different to silicon—CTEs, handling sensitivities, etc.
- The optics of a Fresnel lens concentrator system are *very* different from laboratory tests—non-uniformity, chromatic aberration, lens absorption; design of optics must be matched to multijunction response.
  - Identified top cell as the significant efficiency-limiting aspect of current design
  - Redesigned optics resulted in on-sun >28% lens-cell efficiency at operating temperature

## • Graphics: Amonix 35 kW units before III-V cells

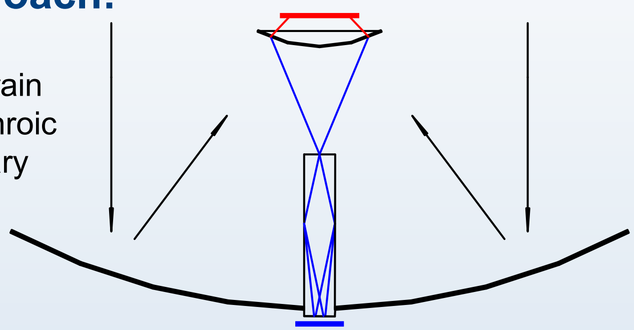
# Toward 40% Hybrid Multi-Junction III-V Terrestrial Concentrator Cells

## PI: Lewis Fraas; JX Crystals Inc.

## • Research Objective:

To demonstrate 40%-efficient hybrid InGaP/GaAs-GaSb multijunction cells in a 33%-efficient Cassegrainian PV concentrator panel.

## • Approach:




## • Industry Impact:

| | TODAY: 15% Silicon Planar Stationary | FUTURE: 33% Cassegrain Module |
|---|---|---|
| Module Cost | \$3.20 / W | \$0.75 / W |
| Tracker Cost | 0 | \$0.25 / W |
| Installation Cost | \$1.50 / W | \$0.75 / W |
| Total Cost per W | \$5.50 / W | \$2.10 |
| KWh per kW per year | 2000 | 2600 |
| Cost per AkWh (A=annual) | \$2.75 per AkWh | \$0.80 per AkWh |
| Cents per kWh (10 year) | 27.5 cents per kWh | 8 cents per kWh |

## • Significant Results:

- Fabricated and tested all components of Cassegrain modules including IR cell and circuit, DJ cell and circuit, dichroic secondary mirror, primary mirror, IR and DJ heat sinks and 25 cm x 25 cm module enclosure.
- Measured efficiency sum of 28.7% at operating temperature

## • Graphics: 3 Cassegrain modules under test

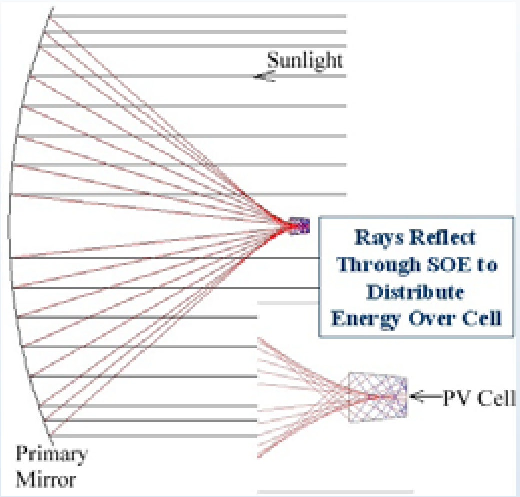
# A Scaleable Reflective Optics High-Concentration PV System

## PI: Stephen Kusek; Concentrating Technologies, LLC

### • Research Objective:

To demonstrate a 33% reflective-optics concentrator module using passively cooled Spectrolab triple-junction cells at 500x.

### • Approach:




### • Industry Impact:

Current single-axis tracking flat-plate silicon systems are over $6/watt installed

Near-term low-megawatt MicroDish production can yield installed costs below $3/watt

System architecture is versatile and allows next-generation HCPV cell as a "drop in" replacement or upgrade

### • Significant Results:

- Spectrolab triple-junction powered units in continuous operation for over one year with no change in performance
- More than 14 W/cm$^2$ from the 2.25 cm$^2$ cell demonstrated
- 500x passive cooling with cell temperatures slightly above flat-plate norms

### • Graphics:

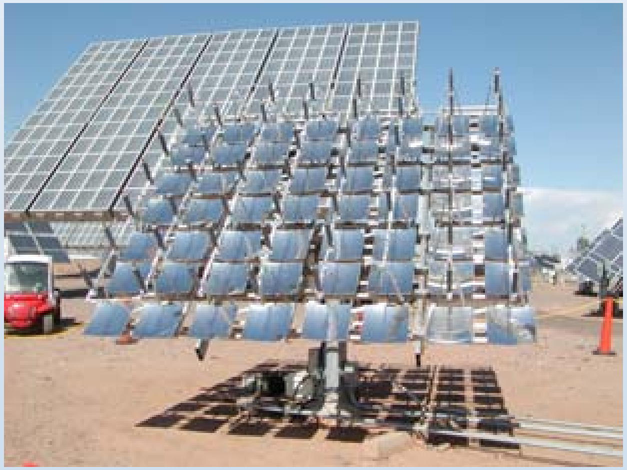
Prototype 1-kW MicroDish system at the Arizona Public Service Solar Technology and Research (STAR) facility

2.25 cm$^2$ cell at about 430x - measured on-sun at 1000W/m$^2$

2002 – 11.7 W/cm$^2$

2004 – 13.7 W/cm$^2$

2005 – 14.4 W/cm$^2$



# Low-Concentration Flat-Plate Module Using High-Efficiency Silicon Cells


## PIs: Richard Swanson, SunPower Corp; Lewis Fraas, JX Crystals Inc.

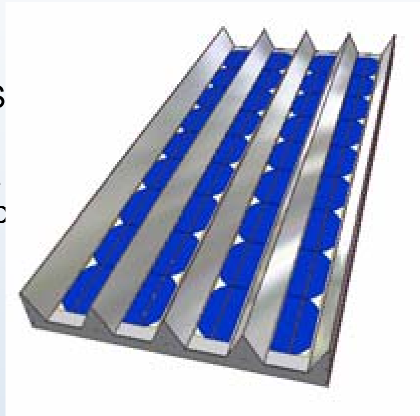

## • Research Objective:

**Opportunity**: The demand for solar photovoltaic cells and modules has far outstripped PV cell supply.

**Solution**: JX Crystals Inc. has a 3-sun mirror module design that uses 1/3 the cells to triple module production at a lower cost.

## • Approach:

1. Cut standard A300 S
cells into thirds.
2. Add aluminum sheet
heat spreader to back c
standard flat-plate
laminant.
3. Add linear mirror
array on front of panel.



## • Industry Impact:

100 kW contracted for demonstration project in Shanghai

## • Significant Results:

| | 3-Sun # 10 | 3-Sun # 7 | Sharp 175 |
|---|---|---|---|
| Voc | 44.51 | 45.25 | 39.95 |
| Isc | 5.75 | 5.74 | 6.11 |
| FF | 0.66 | 0.66 | 0.67 |
| Vmax | 33.82 | 34.39 | 30.36 |
| Imax | 4.98 | 4.98 | 5.35 |
| Pmax, watts | 168 | 171 | 163 |

## • Graphics:

Two 3-sun JXC modules and one Sharp module on 2-axis tracker yielding results shown above.

# Development of IEC Design Qualification Standard for CPV Modules

## PI: Liang Ji, Underwriters Laboratories Inc.

## • Research Objective:

To develop, coordinate, and publish an IEC standard for the design qualification of concentrator photovoltaic (CPV) modules

## • Approach:

1. Contact CPV users and manufacturers to identify the CPV module qualification requirements.
2. Work with IEC/TC82/WG7 committee to improve draft versions.
3. Validate the new procedures agreed by WG7.
4. Submit the draft standard to IEC for official circulation, comments, and voting.

## • Industry Impact:

Both performance and safety design qualification standards for the flat-plate PV modules have already been developed and extensively used by the industry. One potential approach to reduce the cost of solar electricity is the use of CPV modules. The performance design qualification standard development undertaken in this work would benefit the industry to introduce reliable CPV products in the worldwide marketplace.

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## Significant Results:

- Submitted IEC 62108 for international ballot

# High-Efficiency Concentrators

- High-efficiency solar cell concentrator technologies are finally entering world markets
- Two companies with well-developed products, Amonix and Solar Systems, expect to install a total of 15 to 20 MW in 2006
- Many new companies are developing a variety of concentrator concepts
- Next step is incorporating ultra- high-efficiency (>37%) cells

Amonix—United States

Solar Systems—Australia

# Acknowledgements


- DOE Solar Energy Technologies Program for funding and support of these projects
- NREL's Solar Energy Technologies Program (Roland Hulstrom) and National Center for Photovoltaics (Kaz) for their support of the High-Performance PV Project
- The principal investigators and their teams developing and providing their results for this presentation

# Investigation of Approaches to >50% Solar Cells

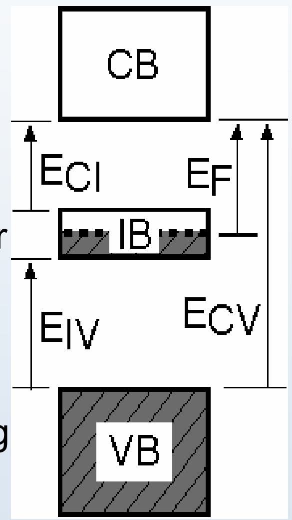
## PI: Christiana Honsberg, University of Delaware

### • Research Objective:

Analyze advanced solar cell efficiency approaches, including realistic loss mechanisms, to determine realistic solar designs >50% efficiency.

### • Approach:

- Develop band-structure models for spherical quantum dot solar cells.
- Determine design rules for material selection of quantum dot multiple-energy-level solar cells.
- Calculate impact of doping on QD energy levels.




### • Industry Impact:

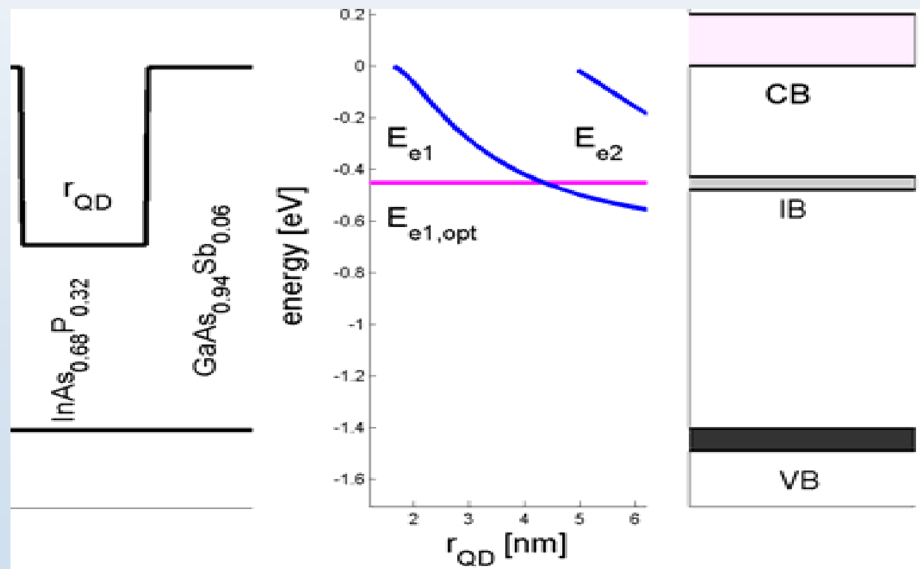
- Identification of design rules and material systems allows practical implementation of quantum dot solar cells.
- QD solar cells give efficiency of 3-junction tandem with two materials.

### • Significant Results:

- Demonstrated that proposed methods to increase efficiency can be grouped into 5 general classes.
- Developed models for band structure of multiple-energy-level quantum dot solar cells.
- Identified two non-idealities to be avoided in multiple-energy-level solar cells: valence band offsets & mini-bands.
- Identified material systems that allow ideal implementation of multiple-energy-level solar cell. All use InP as substrate.

### • Graphics:

Example ideal quantum dot band-structure: $InAs_{0.68}P_{0.32}/GaAs_{0.94}Sb_{0.06}/InP$



# Quantum Dot Solar Cells

## PI: Arthur J. Nozik, NREL (Collaborative Project with Office of Science/BES/Chemical Sciences)

## • Research Objective:

To demonstrate multiple electron-hole pair (exciton) generation from single photons in quantum dots (QDs) and apply this effect to QD solar cells to produce greatly enhanced photocurrent and conversion efficiency

## •Approach:

- Synthesize QDs that are expected to show greatly enhanced multiple exciton generation (MEG).
- Measure MEG using fs transient absorption spectroscopy.
- Develop and characterize nanocrystalline solar cells sensitized with QDs exhibiting efficient MEG and greater photocurrent.
- Model performance of QD solar cells showing efficient MEG.

## • Industry Impact:

Ultra-high conversion efficiency in 3rd-generation solar cells will significantly reduce the cost of PV power.

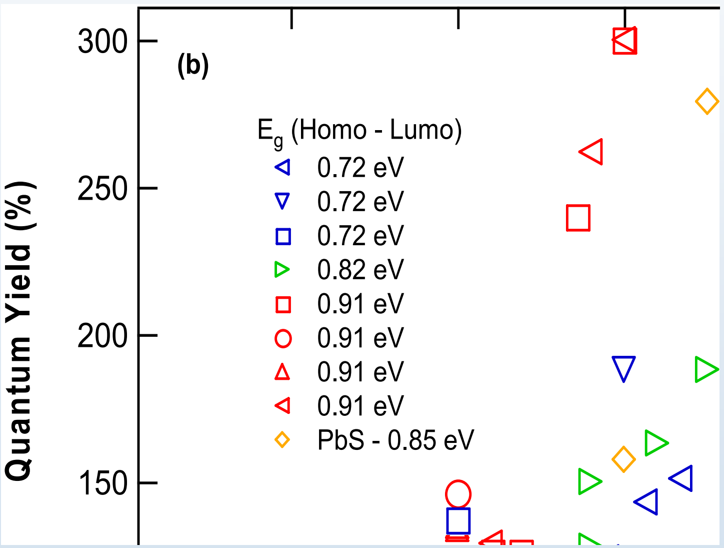
## • Significant Results:

1. Quantum yields of up to 300% (3 electron-hole pairs per photon) have been measured in PbSe and PbS quantum dots at photon energies 4 times the QD bandgap.

2. The enhanced performance and increased efficiency of QD solar cells based on MEG have been calculated.

## • Graphics:

Quantum Yield




Quantum yield vs. photon energy (as ratio of QD bandgap) for PbSe and PbS QDs of different bandgaps (i.e., QD diameters).
(Published in: *NanoLetters*, **5**, 5, 865-871, May, 2005)

# High-Efficiency Multijunction Solar Cells

## PI: Sarah Kurtz, National Renewable Energy Laboratory

## • Research Objective:

Create high-efficiency concentrator cells for low-cost terrestrial photovoltaic applications

## • Approach:

1. **Lattice-matched multijunction**.
   Develop new 1-eV material: GaInNAs.
2. **Lattice-mismatched multijunction**.
   Grow lattice-matched GaInP and GaAs cells first, then mismatched GaInAs cell. Processing requires inversion and substrate removal.
3. **Multijunction on silicon**.
   Active Si junction with III-V top cell.
   Results presented in Paris & Orlando

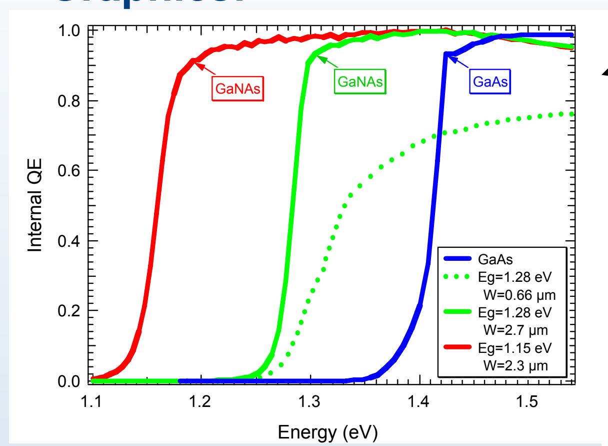
## • Industry Impact:

Once high-efficiency cells are developed, NREL will work with companies to implement these in concentrator systems. NREL also supports industry with a range of projects, studying the effects of changing spectrum on multijunction device design and performance.

## • Significant Results:

- Higher GaInNAs photocurrents obtained for MBE growth
- 37.9% efficiency for early prototype of inverted, lattice-mismatched GaInP/GaAs/GaInAs device, setting a new record

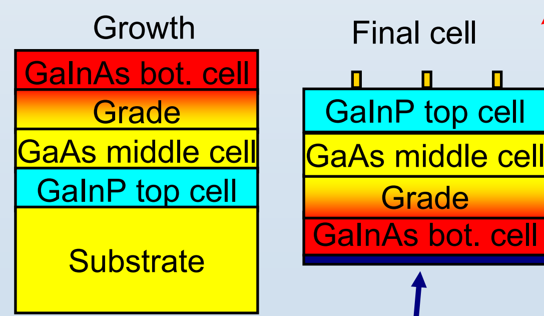
## • Graphics:

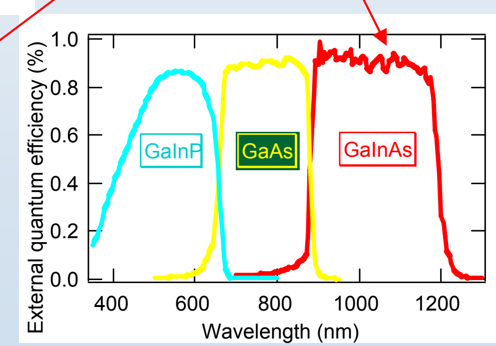



For MBE growth, N does not necessarily degrade the photocurrent.

Data courtesy of A. Ptak

The triple-junction, inverted cell was fabricated for the first time, yielding 37.9%




Patent by M. Wanlass

Metal

*Efficiency @ 10 suns = 37.9%*